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GAS SAMPLING AT THE POINT TUPPER AFBC FACILITY

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GAS SAMPLING AT THE POINT TUPPER AFBC FACILITY

by

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ABSTRACT

A 1 m² pilot-scale bubbling fluidized bed combustor at Point Tupper, Nova Scotia, was operated for about 11,000 h to investigate high temperature corrosion phenomena in coal-fired fluidized bed combustion. During the second last 1000 h segment of this program, in July 1985, the O₂, CO₂, CO, NO_x and SO₂ concentration profiles in the bed and freeboard were measured by extractive gas sampling, under a contract sponsored by Energy, Mines and Resources Canada (EMR). Highly reducing zones were found near the coal feed nozzle and it became apparent that a windbox leak was permitting some of the combustion air to bypass the fluidizing bed. However, the gas species profiles were consistent with those predicted by the plume model of Park, Levenspiel and Fitzgerald.

Subsequently, results obtained from a Nova Scotia Power Corporation (NSPC) extractive gas sampling program became available and these are also presented. Although these show greater variations than those observed in the study for EMR the results of the two studies are in broad agreement. In addition, the NSPC results include measurements taken during the final 1000 h segment of the program for which the windbox leak was sealed. As expected, the gas concentrations then demonstrated considerably more uniform profiles.

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PRÉLÈVEMENT D'ÉCHANTILLONS DE GAZ À L'INSTALLATION DE COMBUSTION
SUR LIT FLUIDISÉ À LA PRESSION ATMOSPHÉRIQUE DE POINT TUPPER

par

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RÉSUMÉ

On a fait fonctionner pendant environ 11 000 heures l'installation pilote de Point Tupper (Nouvelle-Écosse) constituée d'un lit fluidisé à bulles, de 1 m^2 , en vue d'étudier les phénomènes de corrosion à haute température dans les installations de combustion sur lit fluidisé alimentées au charbon. Au cours de l'avant-dernière tranche de 1000 heures de ce programme, en juillet 1985, on a mesuré les profils de concentration du O_2 , du CO_2 , du CO , des NO_x et du SO_2 dans le lit et sur les parois au-dessus du lit, en procédant par prélèvement par extraction d'échantillons de gaz; ces travaux ont été réalisés dans le cadre d'un contrat parrainé par Énergie, Mines et Ressources Canada (EMR). On a trouvé des zones très réductrices à proximité de la tubulure d'alimentation en charbon, et il devint évident que, en raison d'une fuite dans la caisse à vent, une certaine partie de l'air de combustion ne passait pas dans le lit fluidisé. Toutefois, les profils des espèces gazeuses concordaient avec ceux prévus par le modèle de panache de Park, Levenspiel et Fitzgerald.

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Par la suite, les résultats obtenus dans le cadre d'un programme de prélèvement par extraction d'échantillons de gaz, mis en oeuvre par la Nova Scotia Power Corporation (NSPC), sont devenus accessibles; ces résultats, qui sont également présentés, varient bien plus que ceux de l'étude du EMR, mais dans l'ensemble les résultats des deux études concordent entre eux. De plus, les résultats de l'étude de la NSPC comprennent des mesures obtenues au cours de la dernière tranche de 1000 heures du programme, période pendant laquelle la fuite dans la caisse à vent avait été scellée. Comme nous l'avions prévu, les profils de concentration des espèces gazeuses étaient alors beaucoup plus uniformes.

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INTRODUCTION

To reduce the technical risk in building utility-scale atmospheric fluidized bed combustion (AFBC) boilers a 1-m² pilot-scale AFBC combustor was built at Point Tupper, Nova Scotia, and an 11,000 h corrosion test program was carried out involving a number of potential boiler tube materials (1,2). The pilot-scale combustor was built by Combustion Engineering - Superheater Ltd. (CE Canada) and operated by the Nova Scotia Power Corporation (NSPC). The work was funded primarily by Energy, Mines and Resources Canada (EMR) (to the extent of \$8 million) with a contribution of \$550,000 from CE Canada. The metallurgical examination of the alloys was the responsibility of the Physical Metallurgy Research Laboratories (PMRL) of the EMR's Canada Centre for Mineral and Energy Technology (CANMET).

The corrosion test program was carried out in 1000 h segments. For the first seven the primary tool used to characterize the environment surrounding the corrosion specimens was a modified Bosch Lambda oxygen probe (3,4). Subsequently considerable debate arose as to the interpretation of the data from the oxygen probe (5,6), therefore NSPC added a schedule of extractive gas sampling for the last four segments of the program.

However, NSPC was concerned that its extractive gas sampling data might be compromised by the fact that the sampling system had not been specifically designed for in situ extractive gas sampling (7). Consequently EMR accepted a proposal from the University of New Brunswick to fabricate a probe for in situ extractive gas sampling and carry out measurements of O₂, CO₂, CO, NO_x and SO₂ concentrations in the bed and freeboard of the Point Tupper fluidized bed combustor (8,9). It was hoped that these data would help to interpret and validate data from the oxygen probe and the extractive gas sampling carried out by NSPC.

A secondary aim was to provide data that might be of use in developing mathematical models for AFBC, e.g., the attempts to extend the Queen's FBC mathematical model to take into account the finite time for devolatilization currently being undertaken as part of CANMET's contribution to the International Energy Agency (IEA) "Agreement for Cooperation in AFBC" (10,11).

This report is primarily based on a contract report by M. Couturier (9). The construction of the probe and the experimental measurements were subcontracted to the Research and Productivity Council of New Brunswick under the direction of M. Couturier (8).

THE POINT TUPPER FACILITY

The Point Tupper facility has been described in detail in a number of reports (1,2). The combustor is refractory lined, stands approximately 10 m high (Fig. 1), and has a bed area of 1 m^2 . Nine water cooled U-tubes situated within the expanded bed serve to extract heat. The combustor was designed for long-term operation under constant process conditions, including bed temperature and fuel feed rate, therefore provision for varying in-bed cooling was not required.

The front face of the combustor is equipped with a matrix of ports which provide access to the bed for various cooled and uncooled corrosion probes, the Bosch Lamda probe used for oxygen mapping, temperature probes, and extractive sampling probes. For the present study, additional ports were installed to permit extractive gas sampling in the freeboard region.

The combustor is equipped with a pneumatic underbed feed system which admits coal, limestone and recycled material via a single "Tee shaped" nozzle located in the centre of the bed just above the distributor plate. The nozzle is oriented so that solids flow is directed toward two diagonally opposite corners.

Combustion air is supplied by a two stage forced draft (FD) fan, and is heated by a flue-gas-to-air heat exchanger. The flue gas system comprises in addition to the heat exchanger, a cyclone, a baghouse, and an induced draft fan (ID). In addition there is a materials handling plant for coal and limestone preparation, a compressed air system for test specimen cooling, and ash removal facilities. A central control room houses operating controls and data acquisition systems.

The nominal operating conditions are given in Table 1. They were carefully selected in order to simulate a full scale utility boiler.

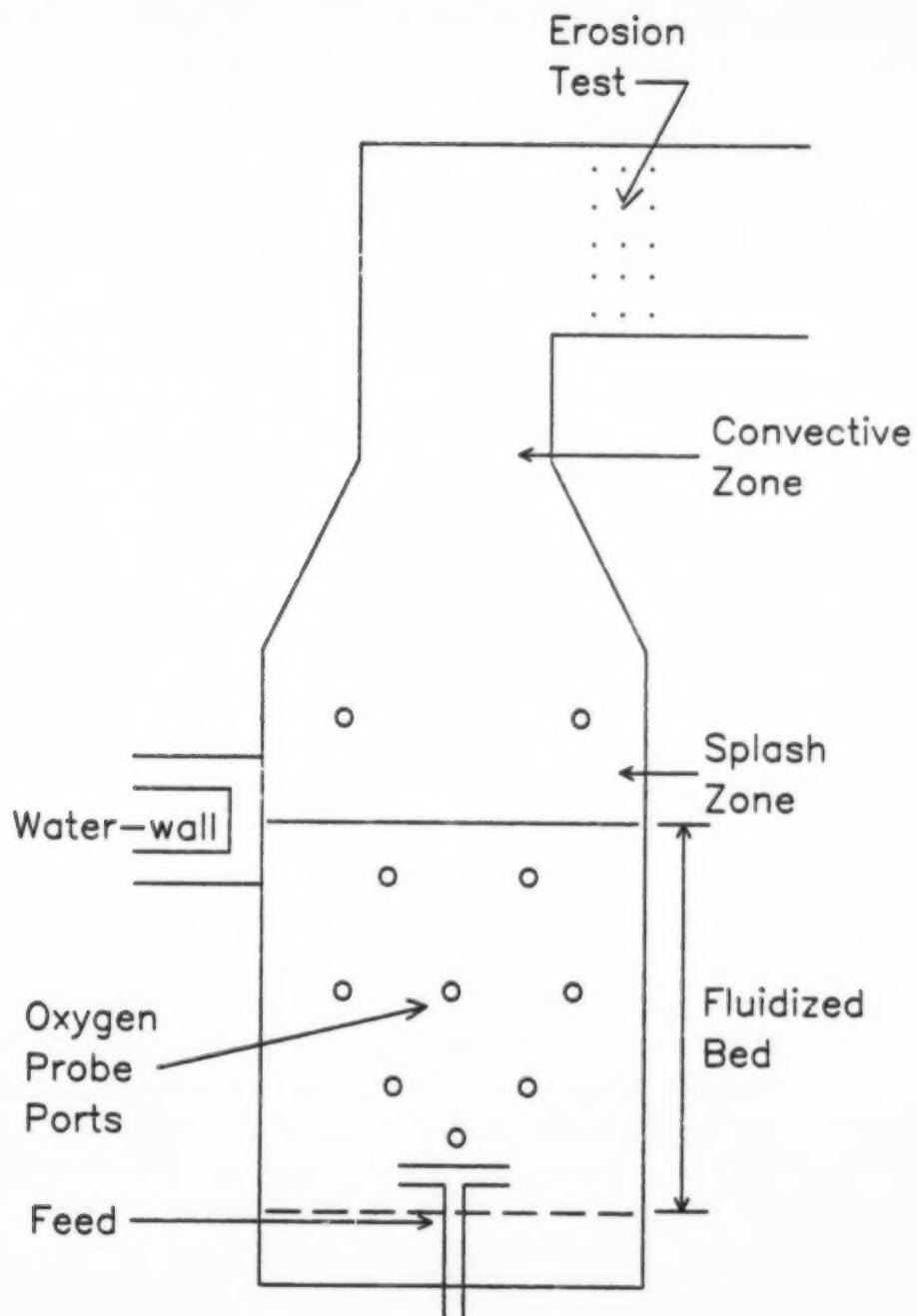


Figure 1 The Point Tupper AFBC Pilot Scale Facility

Table 1 - Nominal operating conditions of the Point Tupper AFBC facility

Thermal rating	1.9 MW
Bed temperature	850°C
Bed area	1 m ²
Expanded bed height	1.22 m
Coal flow	257 kg/h
Coal size	6.35 mm x 0
Limestone flow	44 kg/h
Limestone size	6.35 mm x 0
Recycle rate	2:1
Fuel feed point	one
Superficial gas velocity	2.4 m/s
Excess air	20%

CONSIDERATIONS FOR REPRESENTATIVE SAMPLING IN AN AFBC

The first step in obtaining a meaningful analysis of any flow stream is to obtain a representative sample. Without this the benefits of using advanced analytical instrumentation are negated. In the case of continuous gas sampling there are four major areas of concern:

1. A truly representative sample of the gas stream must be obtained. This means that the sample must be subjected to minimum thermal, chemical or fluid-mechanical disturbances by the sampling system. The latter is particularly important in the case of high velocity streams.

For chemically reacting systems such as combustion systems it is also necessary to ensure that chemical reactions are quenched at the point of sampling unless the sampling and analysis time are intrinsically short when compared with reaction times. This is not the case for conventional analysis in fluidized bed combustion systems hence it is necessary to quench gas phase reactions, particularly when analyzing for minor constituents such as NO_x and CO.

For highly turbulent systems like fluidized beds there are two possible types of measurements - either a method which has a sampling and analysis time significantly greater than the relaxation time associated with chemical and hydrodynamic perturbations of the system, or a method which is intrinsically faster. The first gives a mean concentration whereas the second gives an "instantaneous" measurement which is a function of both the scale and intensity of the turbulent phenomena associated with the system.

In the case of bubbling fluidized bed combustors operating with beds made of coarse particles (>0.5 mm) there is a further complication, namely, that the gas stream may best be described in terms of two phases - emulsion and bubble - which, depending on their relative speeds and the degree of diffusion between them, may have significantly different compositions (12). However, for beds operating with large particles as with the Point Tupper facility this is fortunately not the case.

Gas sampling times will typically be of the order of many seconds while the residence time of a bubble travelling at the superficial gas velocity will be of the order of 0.5 s. This means that any extractive gas sampling method is more naturally suited to obtaining mean concentrations. For this study a sampling time of 10 min was chosen, which may be regarded as an effectively "infinite" sampling period with respect to hydrodynamic processes.

The in situ oxygen probe with a mean response time of about 30 ms, (3) on the other hand, is intrinsically fast compared with hydrodynamic processes. It may be regarded as an "instantaneous" measurement and is well able to distinguish between the emulsion and bubble phases. Both types of measurements are, however, intrinsically slow compared with chemical processes in an AFBC. There is therefore an inherent assumption in such sampling schemes that either the measurement technique may be regarded as a point sink or the spatial variation of species concentration due to chemical processes is insignificant over the region sampled.

2. The sample must be conditioned and transported to the analyzers without altering the concentration ratios of the components to be measured. Conditioning is essential because the analyzers are designed to operate over a narrow tolerance range of temperatures and pressures close to ambient conditions. Furthermore, they are designed to operate with dry, particulate-free, non-corrosive, non-interfering samples. In practice this means that particular care must be taken in gas sample cleanup to remove the particulates that are characteristic of AFBC's, and to remove the excess moisture that might otherwise condense in the sampling lines or analyzer banks.

Another problem is that gaseous species may be partly lost along the transport line because of homogeneous or catalytic reactions or simply by absorption on the walls of the transport system. Condensation and absorption of gas phase species such as SO_2 in the condensate is another possible source of error, while subsequent desorption can lead to erroneously high values when sampling lower concentrations.

3. In order to accurately measure the species of interest the analyzers must also be properly calibrated and maintained. This is particularly important for extensive sampling programs such as the one described in this report.
4. The sample extraction system must be durable because of the high-temperature, corrosive atmosphere present in the combustor. It is also necessary that the gas sampling pump and the analyzers be capable of long periods of operation without repairs.

THE EMR EXTRACTIVE GAS SAMPLING PROGRAM

EXPERIMENTAL SYSTEM

Probe Construction

The details of the probe construction are shown schematically in Fig. 2. An alundum thimble (44.5 mm OD x 127 mm long x 1.5 mm wall thickness supplied by Norton Canada Inc., Hamilton, Ontario) was located at the tip of

ITEM DESCRIPTION

- 1 ALUMINUM FILTER 44.5mm o.d. x 127mm L
- 2 GASKET 52.4mm O.D. x 22.2mm I.D. x 3.2mm THICK
- 3 50.8mm S.S. TUBING, 1.7mm W.T., 2438.4mm L
- 4 44.5mm S.S. TUBING, 1.7mm W.T., 2463.8mm L
- 5 38.1mm S.S. TUBING, 1.7mm W.T., 2641.6mm L
- 6 6.4mm S.S. TUBING, .9mm W.T., 2743.2mm L
- 7 19.1mm S.S. TUBING, 1.7mm W.T., 304.8mm L
- 8 6.4mm S.S. SWAGELOCK REDUCER

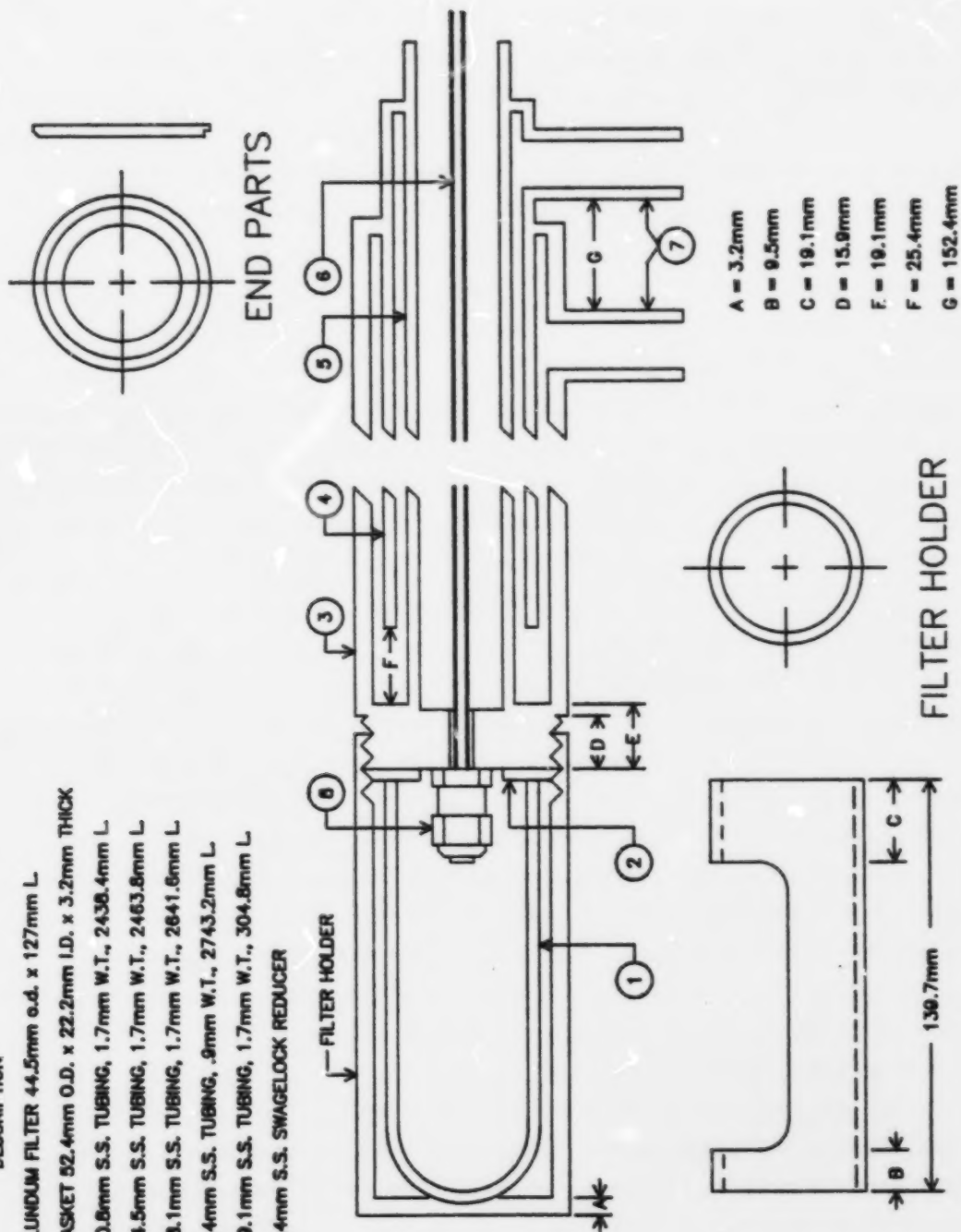


Fig. 2 - Gas sampling probe used for the EMR extractive gas sampling program

GAS SAMPLING PROBE

FIG. 2

the probe for in situ filtering of the solid particles. The filter itself was held in place by a semi-opened stainless steel threaded holder (see Fig. 2) and a high-temperature thread lubricant was used to prevent the threaded parts from seizing.

The probe was water-cooled to ensure structural strength at the high temperatures encountered in the AFBC. However the inner "1/4 in." gas sampling tube was kept at about 150°C by an electrical heating tape (not shown in Fig. 2) wrapped around it. The annulus between the "1/4 in." tube and the next concentric "1 1/2 in." tube was filled with insulation. The temperature of the gas sampling tube was measured by two thermocouples located on its outside wall.

Any solid particles that passed through the alundum filter were prevented from entering the gas sampling line and analytical system by means of a small stainless steel filter located at the rear of the probe. To overcome plugging of the alundum filter there was also provision for purging by means of a compressed air line located at the rear of the probe.

Gas Sampling System

The gas sampling probe was linked by a 24.4 m long electrically heated teflon line to the existing analytical system of the pilot plant. This consisted of a bank of Beckman gas analyzers for CO₂, CO, SO₂ and NO_x and a Teledyne oxygen meter. In some cases, the CO content of the gas exceeded the upper range of the CO analyzer in the existing bank (4000 ppm). Then a second non-dispersive infrared analyzer with an upper range of 5% CO was employed. The teflon line itself was maintained at about 150°C so that no water, sulphuric acid or hydrocarbons would condense along the sampling interface. In addition, all lines and fittings in contact with the gas sample were made of teflon or stainless steel to prevent interferences due to gas adsorption or heterogeneous reactions.

The volumes of the probe and the gas sample (about 2 L/min at STP) were small enough to cause minimal interference to the combustion system. In addition, sample alteration due to relaxation of radical species within the probe was of no concern because free radicals are in very low concentrations at the relatively low operating temperatures of the FBC (800-1000°C). Equally, the quenching by convection within the probe was certainly fast enough that conversion of CO to CO₂ in the sampling probe was negligible. The catalytic

effect of the alundum filter on the sample composition and the effect of any trapped carbon particles on the filter are unknown. However, there is no reason to believe such effects are significant.

The sample transport system had a cold trap located just upstream from the gas analyzers. This removed any hydrocarbons, water and acids in the gas sample. Consequently all the measured gas concentrations were on a moisture-free basis. The pilot plant's analytical system was calibrated and spanned regularly by NSPC personnel during the gas sampling program.

Gas Sampling Procedure

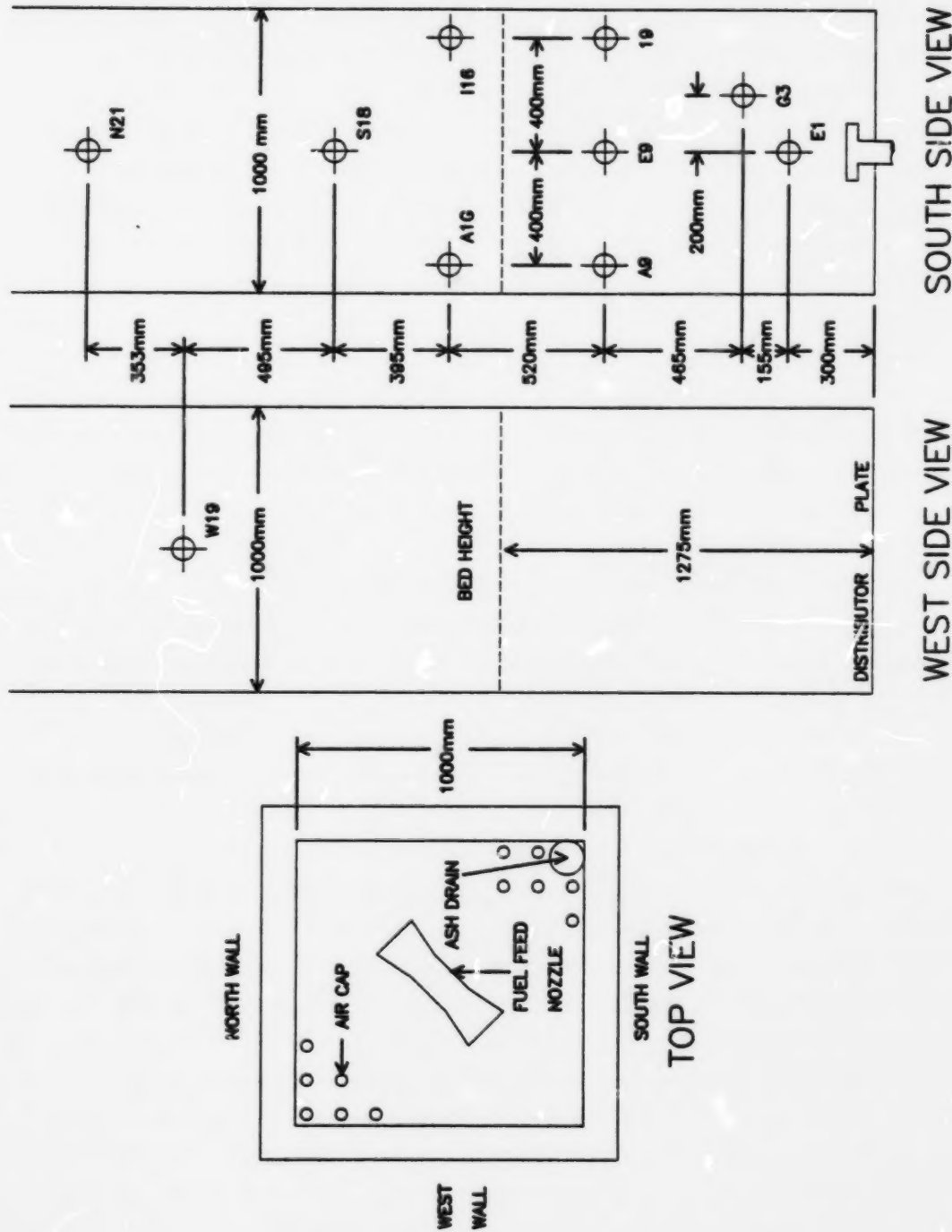
The gas sampling program was carried out during the last 1000-h segment of the corrosion trials from July 23 to 27, 1985. Gas samples were withdrawn from ten sampling ports located along the length of the combustor. Five of the ports were situated in the bed itself, two in the splash zone and the remainder in the freeboard.

The location and labelling of the ports are given in Fig. 3. All the sampling ports except two, designated W19 and N21, were located on the south side of the combustor. Port W19 was located on the west side and port N21 was located on the north side.

At each of the sampling ports, the average concentrations of CO_2 , CO , SO_2 , O_2 and NO_x were determined twice at three equally spaced locations across the combustor, i.e., at 250, 500 and 750 mm from the inside wall of the combustor. The average concentration of a gas species at a given sampling location was obtained by employing the plant's data logging system to record the species' "instantaneous" concentration every minute for a period of ten minutes and then averaging the ten readings. The standard deviation was also calculated and recorded to provide an indication of the magnitude of fluctuations in composition over the ten minute sampling period.

Initially the alundum filter was uncovered. However, the violent periodic upward motion of the bed solids caused excessive breakage of the filters. This problem was solved by shielding the bottom half of the filter using the semi-opened filter holder shown in Fig. 2. It is believed that this had no effect on the composition of the gas samples.

The filters proved to be very effective in separating the gases from solids in situ and the large surface area made it possible to employ large



POSITION AND LABELLING OF THE SAMPLING PORTS
USED IN THE EMR STUDY

FIG. 3

Fig. 3 - Position and labelling of the sampling ports

sample gas flowrates. Plugging was not a significant problem, and in practice the filters were much more likely to crack before they had time to plug. It appeared that the cracking was due to thermal shock associated with introduction or removal of the probe from the combustor. Hence, in order to reduce the amount of time spent replacing filters and maximize their life span, the two sets of readings were obtained consecutively. Thus for the first set of readings the probe was initially positioned 750 mm, then 500 mm and finally 250 mm from the inside wall and the second set of readings was obtained by immediately repeating this procedure before removing the probe from the combustor.

RESULTS

A summary of the results obtained from the EMR program is given in Appendix A. For each port the O_2 , CO_2 , CO , NO_x and SO_2 concentrations were determined at 250, 500 and 750 mm from the inside wall on which the sampling port was located. Two sets of measurements were made at each port and these are denoted in Tables A.1 to A.10 by the designation A and B.

The combustor operating conditions were recorded during the sampling procedure at every location and the overall average operating conditions for the four days during which sampling took place are given in Table 2.

Table 2 - Average operating conditions during the EMR sampling program

	Mean value	Standard deviation
Coal flow (kg/h)	360	36
Limestone flow (kg/h)	60	6.0
Air flow (kg/h)	2825	56
Flue gas O_2 (vol %)	3.03	0.14
Bed temperature ($^{\circ}C$)	851	3.9
Bed height (mm)	1275	14
Recycle rate (kg/h)	513	15

The bed temperature, bed height, air flow and recycle rate showed very little variation during the four days of the sampling program, as indicated by the standard deviations shown in Table 2. However, the coal and limestone feed rates varied by as much as 20% of their mean value.

In general the concentrations of gas species stayed relatively constant over each ten minute sampling period except for ports E1 and G3 which are located relatively close to the feed nozzle. At these ports the gas concentrations, especially of CO, fluctuated over a wide range, as demonstrated by the large standard deviations reported in Tables A.1 and A.2.

DISCUSSION OF RESULTS

Mostly the two sets of measurements at each port were taken consecutively, for reasons previously explained. Exceptions were the measurements in ports A16, I16 and S18, where the replicate measurements were taken 23, 60 and 82 h apart, respectively. Nevertheless, the time-averaged gas concentrations (see Tables A.6, A.7 and A.8) are fairly similar, indicating that the variations in coal and limestone had a relatively small effect.

However, the average concentration of the gas species was strongly influenced by spatial location, both laterally and longitudinally, within the combustor. Thus, the O₂ concentrations within the bed were relatively high in the south-east and north-west corners of the bed and lower elsewhere, almost certainly due to the diagonal north-east and south-west orientation of the "Tee-type" fuel feed nozzle. The readings for traverses in ports I9 and A9 also clearly indicate an increased degree of combustion as the probe moved away from north-west corner and the south-east corner. In addition, there is evidence of some maldistribution of fluidizing air and leakage of air into the bed via channels in the distributor plate seal along the eastern wall of the combustor (4).

It is also clear from the large lateral concentration gradients in the bed that the gases were moving essentially upward through the bed in plug flow with little lateral mixing. Plug flow was further indicated by the fact that the in-bed oxygen concentration decreased with increasing height above the distributor plate (Fig. 4).

These results are in agreement with what one might expect from the plume model proposed by Park et al. (13,14) and further developed by de Kok,

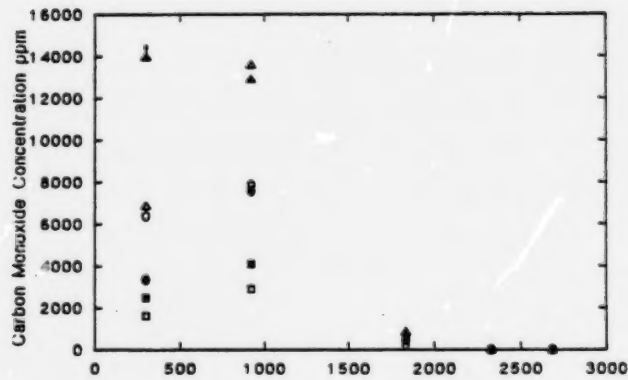


Figure 4a Height Above Distributor Plate, mm

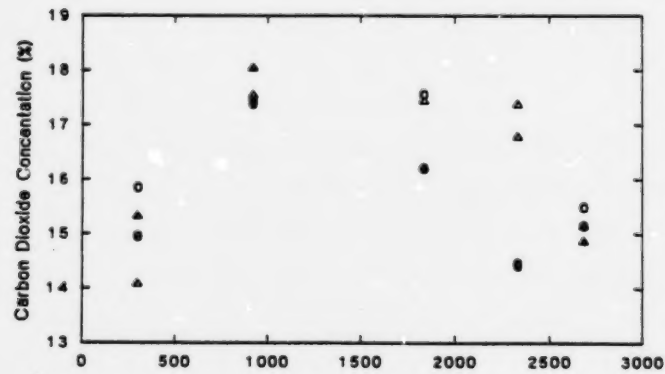


Figure 4b Height Above Distributor Plate, mm

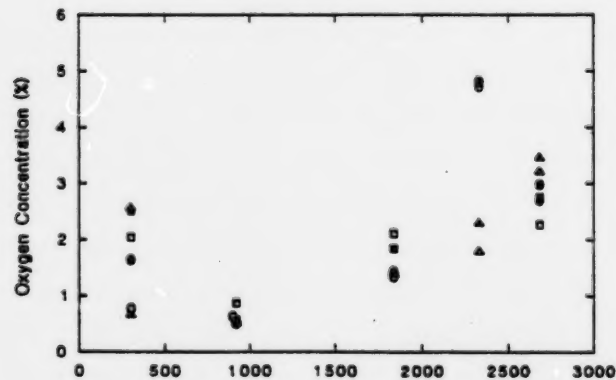


Figure 4c Height Above Distributor Plate, mm

Fig. 4 - O_2 , CO_2 and CO concentrations in middle ports (G3, E9, S18 and N21) versus height above the distributor plate.

Sampling location measured from inside the south wall: $\square$ 750 mm, $\circ$ 500 mm, Δ 250 mm. Measurement series: clear symbols A, dark symbols B.

Nieuwesteeg and van Swaaij (15). These workers have shown that "large particle" AFBC's operate in the slow bubble regime, which implies that the gas flow pattern in AFBC's can be closely approximated by plug flow with little gas concentration difference between the bubble and gas phase. This would mean that despite the inability of extractive gas sampling to distinguish between the bubble and emulsion phases, gas concentration measured at a given location is likely to be representative of both.

Another assumption of the plume model is that devolatilization proceeds rapidly, consequently a plume of volatiles can be expected to arise above the coal feed port, producing local fuel rich regions in the bed where oxygen concentration is significantly lower than elsewhere. This is observed in the north-east and south-west regions of the bed. The results in Table 3 show that in the bed CO and CO₂ are fairly strongly correlated with O₂; CO and CO₂ concentrations are low when O₂ concentrations are high, and vice versa. Furthermore, CO concentrations are highest and most strongly correlated to O₂ concentration where the plume model predicts fuel rich conditions. Examples are results from ports E1, G3 and E9. An exception are the results from port A9, where O₂ concentrations are relatively low, but CO₂ and CO concentrations are not particularly high. The fuel nozzle orientation suggests that this zone is relatively fuel lean.

As shown in Fig. 5 the SO₂ concentrations within the bed generally decrease as a function of height above the distributor plate. Furthermore it can be seen from Table 4 that the SO₂ concentrations are highest in the fuel rich regions of the bed. This indicates that the sulphur content of the "volatiles plume" is relatively high, an observation consistent with the model of Park and Levenspiel (15) for sulphur capture in AFBC'S.

At ports A9 and I9, which can be expected to be somewhat fuel deficient in light of the plume model, SO₂ concentrations are low, and correlation to O₂ concentration is weak. The SO₂/O₂ correlation is likewise weak at ports A16, I16 and N21, where a concentrated volatiles plume is also unlikely. A strong negative effect of O₂ on SO₂ concentrations cannot be explained on chemical grounds, since the sulphation reaction itself is only weakly dependent on oxygen. Where a strong effect is seen, as in the measurements above the fuel nozzle from ports E1, G3 and E9 in the bed, and to a lesser extent from port S18, in the freeboard, it is probably the result of dilution at the edges of a "meandering plume" (13). That is, as the

Table 3 - Correlations of CO and CO₂ with O₂ - EMR Program

Port	Correlation	
	CO	CO ₂
E1	[CO] = 16 902 - 5758[O ₂] r = -0.63	[CO ₂] = 16.00 - 0.50[O ₂] r = -0.66
G3	[CO] = 13 145 - 4325[O ₂] r = -0.43	[CO ₂] = 18.16 - 1.42[O ₂] r = -0.69
A9	[CO] = 2350 - 768[O ₂] r = -0.81	[CO ₂] = 16.12 - 0.002[O ₂]* r = -0.005
E9	[CO] = 20152 - 19560[O ₂] r = -0.59	[CO ₂] = 18.96 - 2.60[O ₂] r = -0.74
I9	[CO] = 1230 - 184[O ₂] r = -0.99	[CO ₂] = 17.01 - 0.84[O ₂] r = -0.999
A16	[CO] = 2857 - 906[O ₂] r = -0.88	[CO ₂] = 18.31 - 0.88[O ₂] r = -0.93
I16	[CO] = 2599 - 785[O ₂] r = -0.93	[CO ₂] = 17.65 - 0.66[O ₂] r = -0.86
S18	[CO] = 1440 - 599[O ₂] r = -0.56	[CO ₂] = 17.39 - 0.40[O ₂]* r = -0.19
W19	--	[CO ₂] = 18.93 - 0.91[O ₂] r = -0.997
N21	--	[CO ₂] = 17.69 - 0.81[O ₂] r = -0.97

*Correlation coefficient, r, indicates no correlation with oxygen concentration.

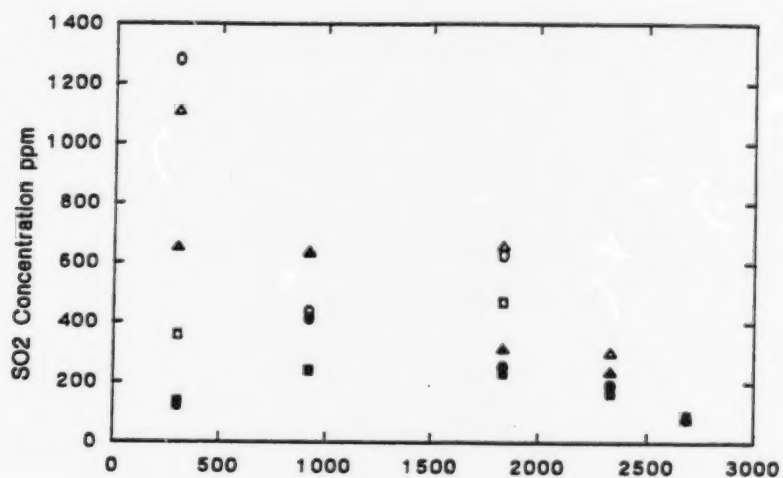


Figure 5a Height Above Distributor Plate, mm

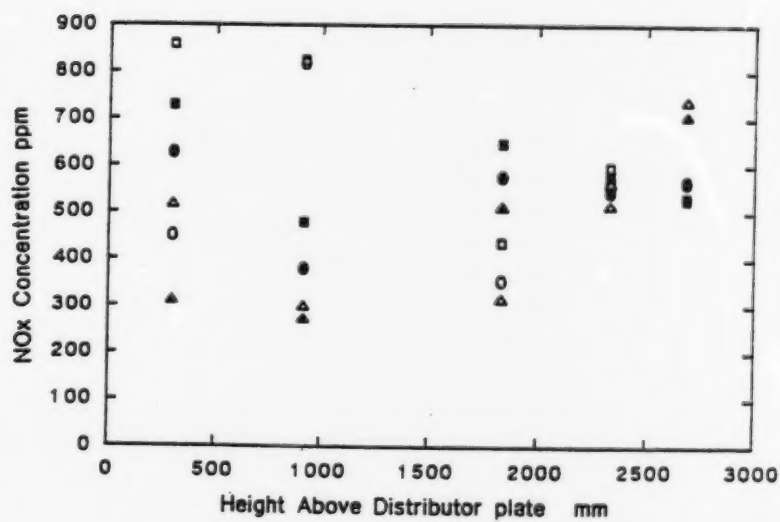


Figure 5b Height Above Distributor Plate, mm

Fig. 5 - NO_x and SO₂ concentrations in middle ports (G3, E9, S18 and N21) versus height above the distributor plate. Sampling locations as measured from inside south wall: □ 750 mm, ° 500 mm; Δ 250 mm. Measurement series: clear symbols A, dark symbols B.

Table 4 - Correlations of NO_x and SO₂ with O₂ - EMR Program

Port	Correlation	
	NO _x	SO ₂
E1	$[\text{NO}_x] = 313 + 159[\text{O}_2]$ $r = +0.67$	$[\text{SO}_2] = 940 - 193[\text{O}_2]^*$ $r = -0.33$
G3	$[\text{NO}_x] = 440 + 123[\text{O}_2]$ $r = +0.65$	$[\text{SO}_2] = 1530 - 279[\text{O}_2]^*$ $r = -0.28$
A9	$[\text{NO}_x] = 548 + 50[\text{O}_2]$ $r = 0.56$	$[\text{SO}_2] = 181 - 44[\text{O}_2]$ $r = -0.86$
E9	$[\text{NO}_x] = -400 + 1368[\text{O}_2]$ $r = +0.90$	$[\text{SO}_2] = 888 - 740[\text{O}_2]$ $r = -0.56$
I9	$[\text{NO}_x] = 971 - 35[\text{O}_2]$ $r = -0.96$	$[\text{SO}_2] = 128 + 0.5[\text{O}_2]^*$ $r = 0.1$
A16	$[\text{NO}_x] = 333 + 46[\text{O}_2]$ $r = +0.47$	$[\text{SO}_2] = 461 - 19[\text{O}_2]^*$ $r = 0.1$
I16	$[\text{NO}_x] = 215 + 134[\text{O}_2]$ $r = +0.97$	$[\text{SO}_2] = 565 - 63[\text{O}_2]^*$ $r = -0.37$
S18	$[\text{NO}_x] = 304 + 107[\text{O}_2]^*$ $r = +0.25$	$[\text{SO}_2] = 623 - 122[\text{O}_2]^*$ $r = 0.20$
W19	$[\text{NO}_x] = 513 + 11[\text{O}_2]$ $r = 0.76$	$[\text{SO}_2] = 323 - 26[\text{O}_2]$ $r = -0.96$
N21	$[\text{NO}_x] = 77 + 182[\text{O}_2]$ $r = +0.84$	$[\text{SO}_2] = 70 + 5[\text{O}_2]$ $r = +0.75$

*Correlation coefficient, r, indicates no correlation with oxygen concentration.

volatile plume rises through the bed, it may shift laterally in a random fashion, parts of it may be occasionally mixed with excess air, and thus effect a dilution of the SO_2 concentrations. A further dilution effect is indicated by the O_2 concentrations measured through port W19. These are shown in Fig. 6, which includes some results from the NSPC extractive gas sampling program. The sharp increase in O_2 concentration, from 1% the west wall to 6% near the east wall, was caused by a leak at the distributor plate which allowed some air to bypass along the east wall.

In general, the NO_x concentrations are lowest in the fuel rich regions of the bed (compare Fig. 4 and 5) and increase with increasing O_2 concentration. This agrees with results reported by other workers. One exception is the results in Table 4 for port I9, which indicate decreasing NO_x with increasing O_2 . This region is fuel lean because of the fuel nozzle orientation, and is furthermore excessively oxygen rich due to an air leak and possible air bypassing on the east wall, as previously discussed. The low NO_x concentrations are therefore believed to be the result of physical dilution, a premise which is supported by the low concentrations of CO_2 , CO and SO_2 in this region. Figure 5 also shows a gradual increase in NO_x up the freeboard, which is probably due to the chemical effects of highly oxidizing zones.

From the wide variation in the correlation coefficients reported in Table 4, it must be concluded first that SO_2 and NO_x concentrations are not strongly dependent on O_2 , and second that major inhomogeneities in gas composition exist in both the bed and freeboard.

Finally, the average O_2 readings in port N21 are in good agreement with those of the platinum-zirconium oxygen sensor located downstream from the cyclone, indicating that relatively little combustion occurred in the upper regions of the freeboard, above port N21.

THE NSPC EXTRACTIVE GAS SAMPLING PROGRAM

GAS SAMPLING SYSTEM AND PROCEDURE

The EMR extractive gas sampling program just described (8,9) was supplemented by a more comprehensive, longer term program carried out by NSPC.

The NSPC sampling system differed from that used in the EMR program primarily in the construction of the probe, which, as shown in Fig. 7 and 8,

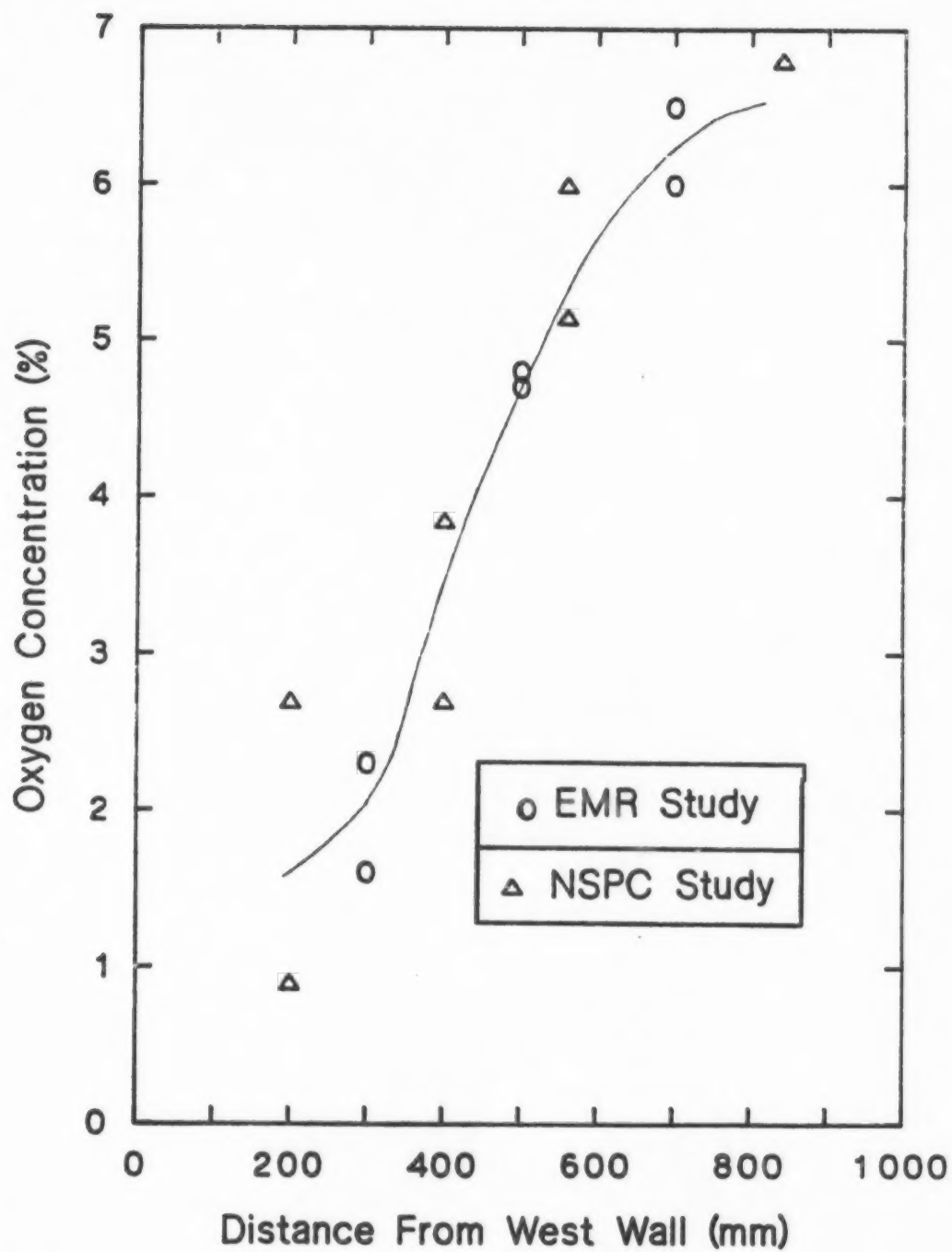


Fig. 6 - Oxygen profile observed at port W19

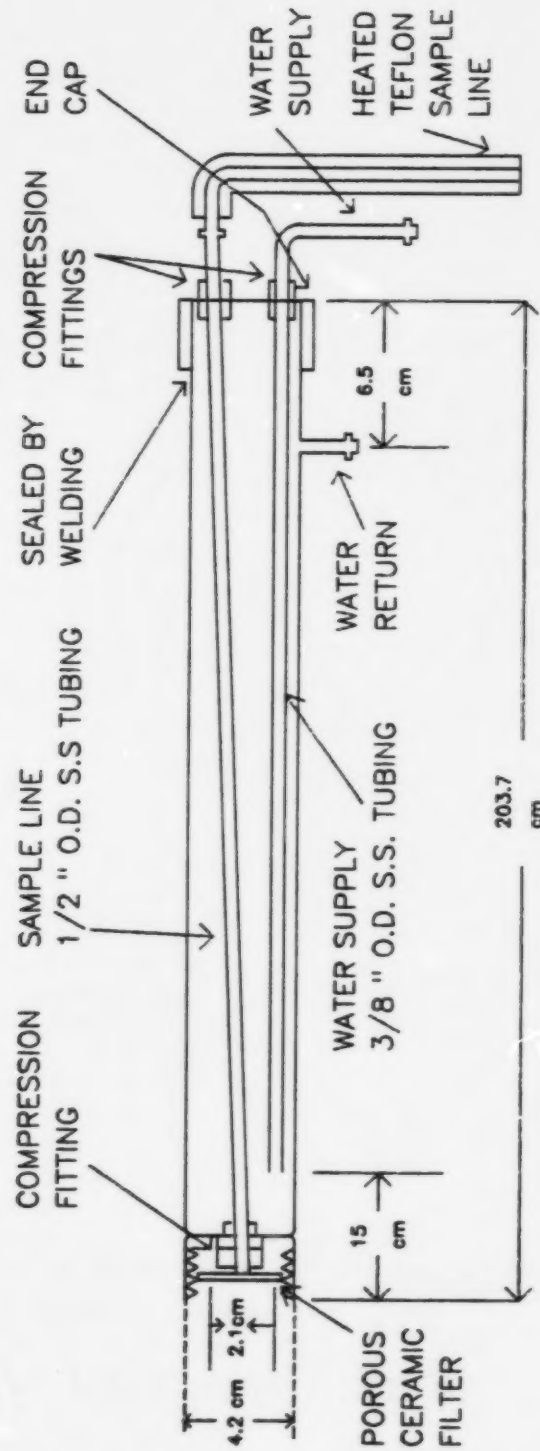


Fig 7 Extractive Probe #1

Fig. 7 - Probe used for the NSPC extractive gas sampling program

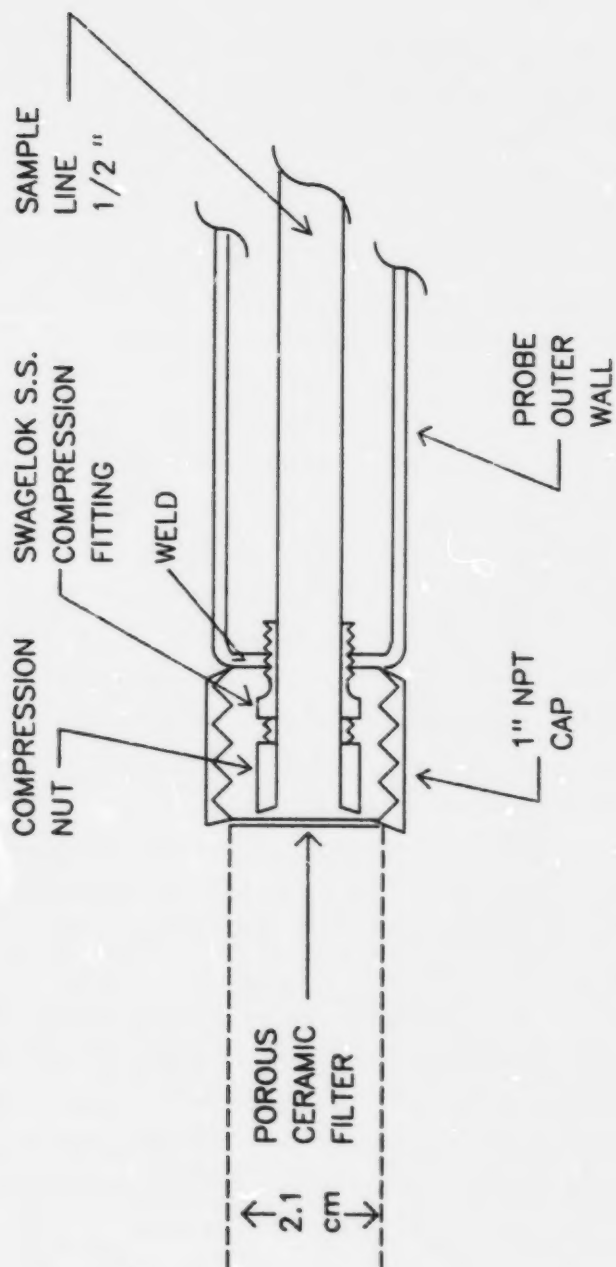


Fig 8. END CAP NSPC PROBE EXPANDED VIEW

Fig. 8 - Details of the end cap of the probe used for the NSPC extractive gas sampling program

had no electrical heating along the sampling tube inside the 2 m long gas passage of the probe. Instead, it was directly water cooled. It was also protected by a smaller ceramic filter. The teflon, line conducting gases to the analyzer bank was held at about 150°C by electrical heating tape. The same bank of gas analyzers was used, i.e., Beckman non-dispersive infra-red analyzers for CO₂, CO and SO₂, a Beckman chemiluminescent analyzer for NO_x, and a Teledyne analyzer for O₂.

Four measurements were taken at each port, at distances of 200, 400, 600 and 800 mm from the inside wall of the combustor. The sampling time at each location was 10 min, with instantaneous readings being recorded at 1 min intervals, which were then averaged to give a mean value.

RESULTS

The NSPC gas sampling program was carried out during the 8th, 9th, 10th and 11th 1000 h segments of the corrosion test program. For convenience, these segments are hereafter referred to as runs 8, 9, 10*, 10 and 11. Run 10* designates the first 750 h of the 10th segment, and during this time the north-east outlet of the fuel nozzle was blocked, which resulted in high O₂ concentrations in that region of the bed. Run 10 designates the last 250 h of the 10th segment, and presents results obtained after the nozzle blockage was discovered and cleared. Two sets of results are given for run 11 as well. Run 11, week 3 presents data obtained after the leaks in the east wall of the combustor had been eliminated, leading to a much more uniform air distribution, whereas run 11, week 4 presents data obtained with a four-way feed nozzle, installed to determine whether more uniform fuel distribution would improve combustion performance.

Results from the NSPC gas sampling program are presented in Appendices B and C. Appendix B contains data from 11 ports in the bed and splash zone, measured during runs 8, 9, 10*, 10, 11 (week 3) and 11 (week 4). It also contains results from one additional port; E1, measured during run 10*. Appendix C contains data from 13 ports in the freeboard, measured during runs 9, 10* and 10. The location of the ports is shown in Fig. 9.

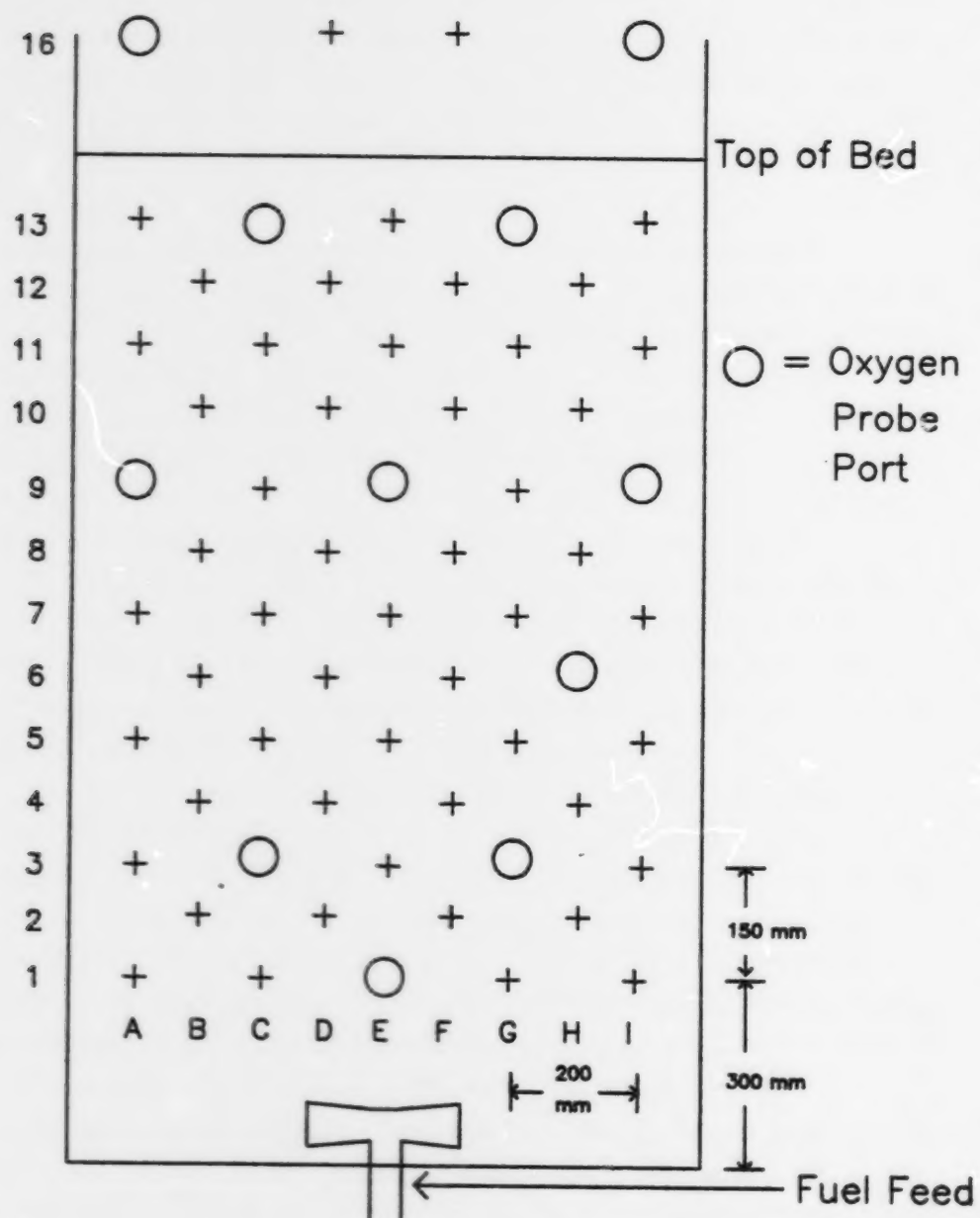


Fig. 9 - Layout of the ports in the south side of the combustor,
used in the NSPC gas sampling program

DISCUSSION OF RESULTS

From a review of the data in Appendix B, it is apparent that results for runs 8, 9 and 10 are not nearly as consistent as those obtained in identical locations during the EMR program. Also, some of the CO_2 readings are anomalously high, e.g., those for ports A9 and E9, initially this was thought to be due to calibration problems, however these values were double checked and the instrument recalibrated each time. The most likely explanation is that these were regions away from the "volatiles plume", but high in calcining limestone. This explanation is supported by the fact that when starting up with a fresh charge of limestone the flue gas CO_2 could go higher than 23%.

In run 10*, the effect of blockage in the north-west-pointed nozzle is strongly apparent, particularly in the lower ports, e.g., E1, C3 and G3. However, by the time the gas stream has traversed half the bed length (600 mm) the disparities due to the blocked nozzle have been significantly reduced. The effects of air leakage into the east side of the combustor remain strong, even at port W19, which is at a height of 2.33 m above the distributor plate (see Fig. 6).

Results for run 11 (week 3), in which the leaks in the east wall of the combustor were sealed, show more uniform oxygen concentrations throughout the combustor. However, the change to a four-way fuel nozzle [run 11 (week 4)] did not produce a strong change in gas concentrations, even low in the combustor at port G3. It also appears that the four-way nozzle tended to run as a three-way nozzle and this may have reflected on G3 values. This was shown by rotating the nozzle and has been discussed in a separate report (17).

Tables 5 and 6 present the correlations of CO and CO_2 with O_2 , and NO_x and SO_2 with O_2 , respectively, excluding data from run 11. Compared with the correlations for the EMR program, presented in Tables 3 and 4, the NSPC data indicated considerably greater scatter, even high into the combustor where the effect of the meandering volatiles plume might be expected to diminish. Nevertheless, there is broad agreement between the results of the two programs. As O_2 increases, NO_x increases, while CO, CO_2 and SO_2 decreases. The trends in CO, CO_2 and NO_x are presumably chemical effects, whereas the trend in SO_2 is most likely explained by physical dilution. The greatest variations in the results are seen either near the feed port, as would be expected, or in the splash zone. In general the results of both programs confirm that there is very little lateral mixing in the combustor; both fuel and air tend to rise as plumes, and gas concentrations reflect this pattern high into the freeboard.

It is also evident that some gas phase reactions are taking place in the freeboard, since a freeboard temperature rise of 90°C or more was measured during the NSPC study.

Table 5 - Correlations of CO and CO₂ with O₂

Port	Correlation	
	CO	CO ₂
E1	[CO] = 8883 - 398[O ₂] r = -0.18	[CO ₂] = 15.71 - 0.81[O ₂] r = -0.99
C3	[CO] = 9215 - 894[O ₂] r = -0.73	[CO ₂] = 17.87 - 0.59[O ₂] r = -0.83
G3	[CO] = 9812 - 655[O ₂] r = -0.81	[CO ₂] = 18.42 - 0.89[O ₂] r = -0.97
B6	[CO] = 8512 - 839[O ₂] r = -0.69	[CO ₂] = 19.37 - 1.07[O ₂] r = -0.99
H6	[CO] = 9772 - 519[O ₂] r = -0.89	[CO ₂] = 19.42 - 1.05[O ₂] r = 0.99
A9	[CO] = 8085 - 1746[O ₂] r = -0.82	[CO ₂] = 19.04 - 1.07[O ₂] r = -0.84
E9	[CO] = 7816 + 96[O ₂]* r = +0.09	[CO ₂] = 19.35 - 1.19[O ₂] r = -0.84
I9	[CO] = 5811 - 121[O ₂]* r = -0.19	[CO ₂] = 19.42 - 1.05[O ₂] r = -0.99
C13	[CO] = 6040 + 1232[O ₂]* r = +0.19	[CO ₂] = 19.75 - 1.33[O ₂] r = -0.35
G13	[CO] = 6351 + 234[O ₂]* r = 0.22	[CO ₂] = 19.26 - 1.23[O ₂] r = -0.90
A16	[CO] = 6751 - 462[O ₂]* r = -0.35	[CO ₂] = 19.25 - 1.07[O ₂] r = -0.93
I16	[CO] = 6030 - 218[O ₂] r = -0.38	[CO ₂] = 19.32 - 1.22[O ₂] r = -0.99

*Correlation coefficient, r, indicates that there is little or no correlation with O₂ concentration.

Table 6 - Correlations between NO_x and SO₂ versus O₂

Port	Correlation	
	NO _x	SO ₂
E1	[NO _x] = 159 + 5.15[O ₂]* r = +0.03	[SO ₂] = 522 - 29.8[O ₂] r = -0.42
C3	[NO _x] = 700 + 12[O ₂]* r = +0.08	[SO ₂] = 759 - 102[O ₂] r = -0.73
G3	[NO _x] = 551 + 61[O ₂] r = +0.55	[SO ₂] = 1090 - 76[O ₂]* r = -0.39
B6	[NO _x] = 322 + 176[O ₂] r = 0.53	[SO ₂] = 1270 - 229[O ₂] r = -0.88
H6	[NO _x] = 935 - 28[O ₂] r = -0.58	[SO ₂] = 1553 - 131[O ₂] r = -0.76
A9	[NO _x] = 149 + 547[O ₂] r = 0.80	[SO ₂] = 917 - 109[O ₂]* r = 0.23
E9	[NO _x] = 639 - 21[O ₂]* r = -0.05	[SO ₂] = 1218 - 207[O ₂]* r = -0.09
I9	[NO _x] = 1197 - 35[O ₂]* r = -0.34	[SO ₂] = 1323 - 149[O ₂] r = -0.85
C13	[NO _x] = 249 + 639[O ₂]* r = 0.36	[SO ₂] = 1196 - 1127[O ₂] r = -0.63
G13	[NO _x] = 772 + 80[O ₂]* r = 0.23	[SO ₂] = 1072 - 156[O ₂]* r = 0.36
A16	[NO _x] = 421 + 161[O ₂] r = 0.47	[SO ₂] = 639 - 3.14[O ₂]* r = 0.02
I16	[NO _x] = 715 + 90[O ₂] r = 0.76	[SO ₂] = 1285 - 275[O ₂] r = -0.77

*Correlation coefficient, r, indicates that there is little or no correlation with O₂ concentration.

CONCLUSIONS FROM THE EMR AND NSPC EXTRACTIVE GAS SAMPLING PROGRAMS

The two studies are in broad agreement and the conclusions are as follows:

1. The gas stream throughout the combustor show little evidence of lateral mixing.
2. The gases are evidently in plug flow indicating that the plume model is a realistic representation of the processes occurring in large AFBC.
3. Attempts to compare the results with those of the in situ oxygen probe were unsuccessful, although the results agreed in trend they did not do so in magnitude.

The results are amongst the most detailed ever gathered for this size of combustor, and hopefully will be of considerable value in developing mathematical models of AFBC processes.

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APPENDIX A

RESULTS FROM THE EMR EXTRACTIVE GAS SAMPLING PROGRAM

Table A.1 - Summary of results for port E1

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	26/7 16:15					
		Average	2.58	14.10	6 900	518	1110
		Std Dev	0.47	0.37	1 400	62	250
	500 mm	26/7 16:01					
		Average	0.77	15.85	6 400	450	1280
		Std Dev	0.22	0.22	1 400	49	100
	750 mm	26/7 15:46					
		Average	2.04	15.67	1 630	858	359
		Std Dev	0.43	0.41	480	38	98
B	250 mm	27/7 01:35					
		Average	0.68	15.34	21 800	313	655
		Std Dev	0.057	0.067	2 800	19	51
	500 mm	27/7 01:29					
		Average	1.64	14.95	3 360	627	126
		Std Dev	0.07	0.11	640	18	20
	750 mm	27/7 01:23					
		Average	2.51	14.94	2 500	728	137
		Std Dev	0.51	0.20	740	34	27

Table A.2 - Summary of results for port G3

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	26/7 12:50					
		Average	1.23	16.61	8 900	576	1190
		Std Dev	0.58	0.22	1 200	32	100
	500 mm	26/7 12:32					
		Average	0.74	17.06	11 400	555	1226
		Std Dev	0.23	0.42	1 700	78	79
	750 mm	26/7 12:17					
		Average	1.08	17.12	9 100	592	964
		Std Dev	0.24	0.34	1 300	55	64
B	250 mm	26/7 13:40					
		Average	1.34	15.88	6 280	641	1049
		Std Dev	0.15	0.27	870	15	75
	500 mm	26/7 13:23					
		Average	1.0	16.4	5 200	514	1610
		Std Dev	0.14	0.24	1 400	34	140
	750 mm	26/7 13:07					
		Average	1.29	16.46	9 100	585	1280
		Std Dev	0.28	0.33	1 300	27	110

Table A.3 - Summary of results for port A9

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	26/7 23:20					
		Average	1.19	16.2	1690	570	129
		Std Dev	0.13	0.11	150	15	11
	500 mm	26/7 23:06					
		Average	1.25	16.28	1130	615.9	103.8
		Std Dev	0.17	0.11	150	6.3	7.5
	750 mm	26/7 22:52					
		Average	2.38	16.29	780	627	81.5
		Std Dev	0.23	0.48	110	26	2.1
B	250 mm	26/7 23:55					
		Average	0.93	16.01	1950	570	161
		Std Dev	0.12	0.08	300	17	17
	500 mm	26/7 23:47					
		Average	1.28	16.14	1030	662	120.2
		Std Dev	0.15	0.056	140	31	4.3
	750 mm	26/7 23:34					
		Average	1.95	15.82	634	692	98.6
		Std Dev	0.20	0.22	67	22	4.5

Table A.4 - Summary of results for port E9

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	26/7 21:11					
		Average	0.58	17.57	13 610	301	640
		Std Dev	0.13	0.26	650	20	40
	500 mm	26/7 20:46					
		Average	0.50	17.44	7 850	379	436
		Std Dev	0.18	0.42	280	20	30
	750 mm	26/7 19:57					
		Average	0.87	16.7	2 910	824	242
		Std Dev	0.19	0.091	440	65	32
B	250 mm	26/7 22:27					
		Average	0.53	18.06	12 930	274	635
		Std Dev	0.03	0.25	490	24	41
	500 mm	26/7 22:06					
		Average	0.63	17.38	7 590	374	415
		Std Dev	0.06	0.19	320	15	30
	750 mm	26/7 21:37					
		Average	0.57	17.03	4 100	478	242
		Std Dev	0.09	0.18	500	25	21

Table A.5 - Summary of results for port 19

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	26/7 18:41					
		Average	6.17	11.93	53	775	108.2
		Std Dev	0.57	0.37	14	35	1.3
	500 mm	26/7 18:20					
		Average	4.14	13.53	460	817	120.7
		Std Dev	0.48	0.36	200	26	9.5
	750 mm	26/7 18:04					
		Average	2.50	14.96	790	880	120
		Std Dev	0.45	0.32	190	25	13
B	250 mm	26/7 19:25					
		Average	6.64	11.44	66	727	142.4
		Std Dev	0.57	0.51	43	29	2.5
	500 mm	26/7 19:11					
		Average	4.84	12.9	320	783	145
		Std Dev	0.41	0.29	140	28	18
	750 mm	26/7 18:56					
		Average	3.44	14.13	600	867	142
		Std Dev	0.59	0.53	270	31	21

Table A.6 - Summary of results for port A16

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	23/7 14:02					
		Average	1.16	17.63	2260	421	691
		Std Dev	0.65	0.13	400	16	37
	500 mm	23/7 14:30					
		Average	3.29	15.50	46	509	432
		Std Dev	0.47	0.40	41	39	56
	750 mm	23/7 14:55					
		Average	0.88	17.73	1220	511	561
		Std Dev	0.13	0.14	430	15	37
B	250 mm	27/7 00:25					
		Average	0.70	17.22	3100	306	539
		Std Dev	0.04	0.097	290	10	48
	500 mm	27/7 00:16					
		Average	1.78	16.37	800	320	249
		Std Dev	0.10	0.088	100	13	33
	750 mm	27/7 00:09					
		Average	0.81	17.84	1900	325	126.8
		Std Dev	0.082	0.91	190	36	9.5

Table A.7 - Summary of results for port I16

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	24/7 12:19					
		Average	3.22	15.45	250	659	348
		Std Dev	0.32	0.31	120	17	16
	500 mm	24/7 12:01					
		Average	3.0	15.61	240	632	361
		Std Dev	0.33	0.098	140	14	23
	750 mm	24/7 11:45					
		Average	1.91	16.96	780	409.1	436
		Std Dev	0.15	0.15	230	8.3	15
B	250 mm	27/7 00:53					
		Average	1.16	16.49	1670	390.8	696
		Std Dev	0.09	0.07	170	8.1	18
	500 mm	27/7 00:46					
		Average	1.19	16.53	1360	381	597
		Std Dev	0.01	0.07	100	17	17
	750 mm	27/7 00:37					
		Average	0.91	17.4	2350	348	241
		Std Dev	0.13	1.3	390	38	58

Table A.8 - Summary of results for port S18

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	24/7 18:28					
		Average	1.46	17.46	890	317	660
		Std Dev	0.072	0.073	230	11	23
	500 mm	24/7 18:11					
		Average	1.34	17.56	240	353.8	628
		Std Dev	0.14	0.12	100	9.5	21
	750 mm	24/7 17:57					
		Average	2.11	16.93	180	435.7	471
		Std Dev	0.17	0.14	120	9.4	30
B	250 mm	25/7 17:09					
		Average	1.405	16.24	880	513	317
		Std Dev	0.095	0.11	210	19	17
	500 mm	25/7 16:52					
		Average	1.43	16.2	470	576	253
		Std Dev	0.17	0.15	130	21	18
	750 mm	25/7 16:37					
		Average	1.84	16.06	237	647	234
		Std Dev	0.094	0.13	64	30	25

Table A.9 - Summary of results for port W19

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	24/7 20:54					
		Average	2.31	16.8	8	564	240
		Std Dev	0.14	0.16	21	12	12
	500 mm	24/7 20:37					
		Average	4.81	14.46	0	565.4	192.0
		Std Dev	0.29	0.26	0	7.7	4.5
	750 mm	24/7 20:22					
		Average	6.02	13.59	0	597	175.5
		Std Dev	0.42	0.35	0	12	3.3
B	250 mm	24/7 21:56					
		Average	1.81	17.39	55	517	304
		Std Dev	0.18	0.27	86	16	40
	500 mm	24/7 21:37					
		Average	4.72	14.42	0	544	190.6
		Std Dev	0.27	0.22	0	14	6.8
	750 mm	24/7 21:19					
		Average	6.45	13.1	0	580	166.2
		Std Dev	0.36	0.33	0	14	6.5

Table A.10 - Summary of results for port N21

Position	Date	Time	Gas species concentration				
			O ₂ %	CO ₂ %	CO ppm	NO _x ppm	SO ₂ ppm
A	250 mm	25/7 01:09					
		Average	3.23	15.17	0	740	85.1
		Std Dev	0.26	0.19	0	23	1.5
	500 mm	25/7 12:52					
		Average	2.70	15.49	0	564	82.8
		Std Dev	0.32	0.25	0	21	2.1
	750 mm	25/7 12:34					
		Average	2.27	15.92	2.8	533	82.1
		Std Dev	0.33	0.33	8.8	15	3.0
B	250 mm	25/7 01:57					
		Average	3.48	14.88	0	708	89.7
		Std Dev	0.28	0.29	0	26	1.9
	500 mm	25/7 01:41					
		Average	2.98	15.15	0	567	87.3
		Std Dev	0.24	0.21	0	15	1.6
	750 mm	25/7 01:25					
		Average	2.76	15.37	0	528	87.8
		Std Dev	0.29	0.24	0	10	2.4

APPENDIX B

RESULTS FROM THE NSPC EXTRACTIVE GAS SAMPLING PROGRAM
IN THE BED AND SPLASH ZONE

NOTE: Runs 8, 9, 10 and 11 correspond to the 8th, 9th, 10th and 11th 1000 h segments of the corrosion test program. Run 10* designates the first 750 h of the 10th segment, and during this time the north-east outlet of the fuel nozzle was blocked, which resulted in high O_2 concentrations in that region of the bed. Run 10 designates the last 250 h of the 10th segment, and presents results obtained after the nozzle blockage was discovered and cleared. Run 11 (week 3) presents data obtained after the leak in the east wall had been sealed, leading to a much more uniform air distribution. Run 11 (week 4) presents data obtained with a four-way feed nozzle, installed to determine whether a more uniform fuel distribution would improve combustion performance.

Table B.1 - Summary of results for port E1

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	10*	14.5	4.12	6004	36	174
400 mm	10*	16.25	2.5	2691	259	33
600 mm	10*	14.1	4.17	1529	377	42
800 mm	10*	15.33	3.41	1373	273	48

*Result for blocked nozzle.

Table B.2 - Summary of results for port G3

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	5.2	14	6000	650	550
	9	6.0	13.11	5380	996	775
	10*	4.2	14.1	7620	982	589
	10	-	-	-	-	-
	11 (wk 3)	15.1	6.20	3725	-	80
	11 (wk 4)	11.5	8.26	6138	-	193
400 mm	8	2.7	16.5	7900	850	>1000
	9	1.25	17.33	8261	422	>1000
	10*	-	-	-	147	-
	10	-	-	-	-	-
	11 (wk 3)	13.05	7.89	5400	-	98
	11 (wk 4)	9.4	9.41	8300	-	340
600 mm	8	3.6	15.5	9000	650	1000
	9	1.45	17.11	9380	760	-
	10*	-	-	-	-	-
	10	-	-	-	-	-
	11 (wk 3)	7.74	10.22	7250	-	356
	11 (wk 4)	8.26	8.26	6138	-	193
800 mm	8	-	-	-	-	-
	9	2.68	15.6	7211	760	-
	10*	-	-	-	-	-
	10	-	-	-	-	-
	11 (wk 3)	12.92	8.45	7390	-	643
	11 (wk 4)	13.0	6.7	5500	-	40

*Results for blocked nozzle.

Table B.3 - Summary of results for port C3

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	0.8	18.0	9 500	100	850
	9	-	-	-	-	-
	10*	2.5	15.37	9 842	474	853
	10	-	-	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	14.0	12.91	8 665	540	-
400 mm	8	2.9	16.0	7 500	800	>1000
	9	-	-	-	-	-
	10*	0.89	17.28	8 448	830	556
	10	-	-	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	2.6	14.97	10 500	-	1500
600 mm	8	2.5	17	5 000	1100	550
	9	-	-	-	-	-
	10*	1.3	16.75	5 945	1115	275
	10	-	-	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	4.66	13.19	9 400	-	1000
800 mm	8	5.8	16	2 100	800	50
	9	-	16.06	-	-	-
	10*	6.7	12.87	4 470	663	97
	10	-	13.73	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-

*Results for blocked nozzle.

Table B.4 - Summary of results for port H6

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	9.9	10	4 100	700	250
	9	9.34	9.95	4 260	835	96
	10*	9.55	8.84	5 124	749	148
	10	9.3	9.47	6 419	-	341
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
400 mm	8	6.5	13.0	5 700	650	550
	9	5.27	13.85	6 579	835	1558
	10*	9.3	9.24	4 790	768	67
	10	7.8	11.06	6 880	-	346
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
600 mm	8	5.6	14.0	7 000	700	900
	9	3.0	15.84	76 505	704	-
	10*	9.7	8.88	3 978	800	15
	10	6.3	12.48	7 440	-	487
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
800 mm	8	5.6	14.5	6 600	850	850
	9	5.72	13.05	6 271	704	1155
	10*	15.1	3.55	1 582	270	64
	10	6.7	12.12	7 292	-	534
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-

*Results for blocked nozzle.

Table B.5 - Summary of results for port B6

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	1.0	18.5	8000	300	1000
	9	0.62	18.43	8199	100	1275
	10*	1.4	18.22	9320	147	862
	10	1.7	17.77	7493	-	891
	11 (wk 3)	-	-	-	-	411
	11 (wk 4)	-	-	-	-	-
400 mm	8	2.4	16.5	6800	1050	950
	9	0.53	18.58	8217	435	1330
	10*	2.2	16.95	8720	185	631
	10	3.9	14.96	5674	-	516
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
600 mm	8	1.8	17.5	5200	1250	550
	9	1.38	17.74	6305	1184	1260
	10*	3.1	16.14	6642	433	408
	10	3.9	14.88	4165	-	288
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
800 mm	8	3.7	16.0	2800	1200	150
	9	3.18	16.06	3499	1184	259
	10*	5.6	12.87	4947	1123	203
	10	5.6	13.73	4963	-	141
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-

*Results for blocked nozzle.

Table B.6 - Summary of results for port A9

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	0.70	17.5	6200	600	>1000
	9	0.44	18.7	6990	95	1032
	10*	0.31	21.6?	8548	107	872
	10	-	-	-	-	-
	11 (wk 3)	0.35	19.06	4688	-	-
	11 (wk 4)	0.30	17.23	4560	409	409
400 mm	8	2.0	16.5	6100	900	>1000
	9	0.64	18.47	6496	759	1375
	10*	0.36	19.14	8260	200	646
	10	-	-	-	-	-
	11 (wk 3)	2.12	17.8	5977	-	555
	11 (wk 4)	0.6	-	6750	-	656
600 mm	8	1.7	17.0	4800	1100	700
	9	1.1	18.06	6031	1173	868
	10*	0.8	17.85	6670	548	333
	10	-	-	-	-	-
	11 (wk 3)	2.73	16.32	3760	-	207
	11 (wk 4)	1.12	17.17	7210	-	815
800 mm	8	2	17.50	4200	1150	750
	9	1.23	17.92	4949	1173	737
	10*	-	17.44	5873	1000	148
	10	-	-	-	-	-
	11 (wk 3)	2.4	17.35	1520	-	212
	11 (wk 4)	0.43	17.47	6206	-	703

*Results for blocked nozzle.

Table B.7 - Summary of results for port E9

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	1.10	19.0	8200	550	>1000
	9	0.16	19.61	8037	323	1650
	10*	0.41	18.83	9048	549	706
	10	-	-	-	-	-
	11 (wk 3)	1.54	17.35	6400	-	333
	11 (wk 4)	-	-	-	-	-
400 mm	8	2.20	16.50	7800	700	>1000
	9	0.66	18.40	7943	1027	2100
	10*	0.41	18.23	8685	453	532
	10	-	-	-	-	-
	11 (wk 3)	5.44	14.14	7250	-	467
	11 (wk 4)	-	-	-	-	-
600 mm	8	0.90	18.0	8000	350	1000
	9	0.21	19.15	7505	921	1570
	10*	0.34	18.35	7557	711	406
	10	-	-	-	-	-
	11 (wk 3)	6.26	12.64	6400	-	318
	11 (wk 4)	6.00	-	-	-	-
800 mm	8	0.6	19.00	7000	300	850
	9	0.11	19.36	6885	921	1360
	10*	-	14.66	6372	1146	202
	10	-	-	-	-	-
	11 (wk 3)	4.85	13.82	6242	-	316
	11 (wk 4)	-	-	-	-	-

*Results for blocked nozzle.

Table B.8 - Summary of results for port I9

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	8.4	11.0	3800	850	250
	9	5.5	13.89	3586	1005	565
	10*	7.0	11.93	6444	1048	261
	10	-	-	-	-	-
	11 (wk 3)	1.9	15.5	-	-	111
	11 (wk 4)	0.50	16.28	-	230	780
400 mm	8	6.7	12.5	4500	700	400
	9	4.24	15.03	4666	1041	734
	10*	5.50	13.12	7743	1442	203
	10	-	-	-	-	-
	11 (wk 3)	1.3	16.5	4300	-	811
	11 (wk 4)	0.43	16.85	6000	-	752
600 mm	8	5.9	13.50	5400	750	550
	9	3.8	15.49	5548	1083	1080
	10*	7.3	11.70	5529	1055	80
	10	-	-	-	-	-
	11 (wk 3)	0.8	16.69	4560	-	555
	11 (wk 4)	0.56	16.89	6650	-	761
800 mm	8	3.5	16.00	5300	1000	750
	9	2.3	16.92	5190	1083	861
	10*	7.1	11.67	3916	928	124
	10	-	-	-	-	-
	11 (wk 3)	1.53	15.83	4025	-	644
	11 (wk 4)	0.35	15.81	5615	-	270

*Results for blocked nozzle.

Table B.9 - Summary of results for port C13

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	0.40	21.04?	7400	200	71 000
	9	0.05	20.12	6480	108	1 300
	10*	0.53	21.04?	8460	207	777
	10	-	-	-	-	-
	11 (wk 3)	0.60	19.75	6500	-	387
	11 (wk 4)	0.76	17.25	7990	330	522
400 mm	8	0.40	19.00	7200	800	950
	9	0.14	19.80	6202	328	965
	10*	0.60	19.81	7493	330	545
	10	-	-	-	-	-
	11 (wk 3)	1.48	17.84	6300	-	396
	11 (wk 4)	1.7	15.86	8100	-	442
600 mm	8	0.40	19.00	6500	650	700
	9	0.38	18.97	5464	715	965
	10*	0.35	19.82	6055	398	382
	10	-	-	-	-	-
	11 (wk 3)	0.67	19.23	6300	-	471
	11 (wk 4)	1.86	15.75	7700	-	385
800 mm	8	-	19.00	5900	600	550
	9	0.52	18.59	5045	715	772
	10*	0.47	18.69	5360	999	273
	10	1.1	-	-	-	-
	11 (wk 3)	1.1	18.12	5165	-	316
	11 (wk 4)	1.53	16.32	6577	-	342

*Results for blocked nozzle.

Table B.10 - Summary of results for port G13

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	1.9	17.0	6000	900	800
	9	1.2	17.83	5690	692	1240
	10*	2.6	16.20	7742	996	458
	10	-	-	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
400 mm	8	1.5	17.0	6900	650	1000
	9	1.9	17.18	5245	747	1265
	10*	2.1	16.94	7582	1070	628
	10	-	-	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
600 mm	8	0.90	18.0	7100	550	1000
	9	0.77	18.32	7123	1065	1265
	10*	1.80	16.63	7135	1169	55
	10	-	-	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
800 mm	8	0.60	19.50	6700	500	800
	9	0.09	18.89	6239	1045	849
	10*	1.30	17.07	6662	1204	411
	10	-	-	-	-	-
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-

*Results for blocked nozzle.

Table B.11 - Summary of results for port A16

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	0.20	20.0?	5800	50	700
	9	0.13	19.82	6422	53	683
	10*	0.23	21.90?	8820	365	638
	10	0.48	19.26	6049	-	566
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	1.0	16.90	6168	220	371
400 mm	8	0.20	18.50	6600	300	>1000
	9	1.10	18.30	5167	653	>2500
	10*	0.37	19.69	8739	887	742
	10	1.90	17.18	6128	-	665
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	1.00	16.72	6500	-	315
600 mm	8	0.50	18.0	7100	100	900
	9	3.20	15.94	4016	779	877
	10*	2.70	16.38	7804	948	579
	10	2.70	16.17	5083	-	347
	11 (wk 3)	2.10	-	-	-	-
	11 (wk 4)	1.20	16.64	6177	-	292
800 mm	8	0.50	18.50	4500	800	650
	9	0.44	18.60	5539	779	916
	10*	0.34	18.55	7398	940	275
	10	0.39	18.53	5740	-	367
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	1.28	16.35	5850	-	285

*Results for blocked nozzle.

Table B.12 - Summary of results for port I16

Position	Run	Gas species concentration, dry gas basis				
		O ₂ % vol	CO ₂ % vol	CO ppm vol	NO _x ppm vol	SO ₂ ppm vol
200 mm	8	0.80	18.50	6100	700	1000
	9	2.90	16.22	3728	1061	829
	10*	2.90	15.34	6850	1095	175
	10	-	17.46	6755	-	72
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
400 mm	8	1.10	18.00	5500	1000	900
	9	1.80	17.34	5334	996	996
	10*	3.70	14.51	6166	981	254
	10	3.60	15.21	5268	-	262
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
600 mm	8	0.60	18.50	6300	650	1000
	9	0.67	18.46	6034	635	-
	10*	5.10	13.18	4736	1067	78
	10	3.00	15.88	4949	-	202
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-
800 mm	8	0.60	18.50	5400	900	900
	9	0.36	18.89	6725	635	1983
	10*	3.40	1.481	5674	1012	534
	10	1.70	17.11	4656	-	212
	11 (wk 3)	-	-	-	-	-
	11 (wk 4)	-	-	-	-	-

*Results for blocked nozzle.

APPENDIX C

RESULTS FROM THE NSPC EXTRACTIVE GAS SAMPLING PROGRAM
IN THE FREEBOARD REGION

NOTE: Runs 9 and 10 correspond to the 9th and 10th 1000 h segments of the corrosion test program. Run 10* designates the first 750 h of the 10th segment, and during this time the north-east outlet of the fuel nozzle was blocked, which resulted in high O_2 concentrations in that region of the bed. Run 10 designates the last 250 h of the 10th segment, and presents results obtained after the nozzle blockage was discovered and cleared.

Table C.1 - O₂ measurements, % volume, dry gas basis

Port	Height mm	Probe position							
		200 mm	400 mm	600 mm	800 mm				
A17	1540	0.5*	0.95**	0.66	2.39	1.8	0.91	2.7	1.2 2.0 1.7 3.7 2.5
E17	1540	1.76	1.3	1.9	1.94	1.1	3.1	1.45	3.1 3.3 2.6 6.7 4.2
I17	1540	5.2	5.1	4.6	5.0	7.2	6.4	8.8	7.4 5.8 8.3 8.1 5.5
W17-N	1540	4.7	4.4		5.3	6.8		3.8	10.4 4.6 6.9
W17-S	1540	5.1	1.2		5.5	1.0		5.2	1.7 6.7 3.3
S17.5	1744	0.3**			0.52**			0.67**	3.3**
S18	1835	3.1	0.7	2.9	2.67	1.4	2.9	2.79	2.6 3.4 3.4 5.2 5.6
W19	2330	2.67	0.96		3.86	2.7		5.18	6.0 6.82 8.2
N20	2657	5.3*			3.7*			4.1*	4.1*
N21	2683	4.5			6.1			3.5	3.4
CZN ^Δ	4050	4.8			5.8			6.3	7.2
CZC ^Δ	4050	5.5			5.8			5.7	6.6
CZS ^Δ	4050	3.7			4.5			5.7	6.4

*Run 9.

**Run 10* - nozzle blocked.

Remaining data: run 10 - nozzle clear.

^ΔPorts in top of combustor, west wall, near entrance to convective zone.

Table C.2 - CO₂ measurements, % volume, dry gas basis

Port	Height mm	Probe position											
		200 mm			400 mm			600 mm			800 mm		
A17	1540	18.55*	19.24**	18.05	16.65*	17.26**	17.70	16.05**	17.62**	16.55	16.95*	15.35**	16.15
E17	1540	16.67	17.80	16.78	16.26	17.94	15.51	16.76	15.64	15.24	15.63	12.11	14.47
I17	1540	13.11	13.61	14.05	13.31	11.58	12.23	10.33	11.33	12.76	11.13	10.61	13.10
W17-N	1540	14.41*	14.23**		13.87*	11.74**		15.39**	8.14**		14.05*	11.83**	
W17-S	1540	14.25	18.17		13.95	17.42		14.04	16.86		12.43	14.60	
S17.5	1744	18.55**			17.90**		17.79**				15.35**		
S18	1835	15.93	17.70	15.63	16.34	16.72	15.71	16.25	15.68	15.23	15.61	13.17	12.97
W19	2330	16.41	17.61		15.20	15.87		14.97	12.59		15.02	10.33	
N20	2657	13.78*			15.20*		14.97*				15.02*		
N21	2683	14.44			15.37		15.60				15.70		
CZN ^Δ	4050	14.46			13.34		13.04				12.36		
CZC ^Δ	4050	13.90			13.39		13.51				12.72		
CZS ^Δ	4050	15.48			14.70		13.59				12.96		

*Run 9.

**Run 10* - nozzle blocked.

Remaining data: run 10 - nozzle clear.

^APorts in top of combustor, west wall, near entrance to convective zone.

Table C.3 - NO_x measurements, ppm volume, dry gas basis

Port	Height mm	Probe position							
		200 mm		400 mm		600 mm		800 mm	
A17	1540	988*	250**	968*	278**	893**	943**	972*	908**
E17	1540	899	695	965	652	998	873	978	676
I17	1540	866	779	840	732	588	735	598	752
W17-N	1540	864*	831**	675*	812**	567**	762**	709*	772**
W17-S	1540	682	173	630	722	533	650	673	870
S17.5	1744	826**		706**		953**		1161**	
S18	1835	761	873	863	828	805	770	783	663
W19	2330	644	796	592	733	595	652	544	541
N20	2657	511*		576*		550*		559*	
N21	2683	484		463		460		449	
CZN ^Δ	4050	379		362		343		338	
CZC ^Δ	4050	426		373		382		381	
CZS ^Δ	4050	401		373		374		348	

*Run 9.

**Run 10* - nozzle blocked.

Remaining data: run 10 - nozzle clear.

^ΔPorts in top of combustor, west wall, near entrance to convective zone.

Table C.4 - SO₂ measurements, ppm volume, dry gas basis

Height		Probe position											
Port	mm	200 mm		400 mm		600 mm		800 mm					
A17	1540	988*	906**	566	691*	620**	481	606**	752**	356	526*	367**	244
E17	1540	561	660	442	596	670	312	555	382	265	297	114	233
I17	1540	276	294	412	232	91	165	168	21	166	152	15	182
W17-N	1540	451*	79**		539*	43**		2040**	40**	718*	23**		
W17-S	1540	324	692		457	594		795	738	391	590		
S17.5	1744	514**			401**			235**		120**			
S18	1835	318	501	259	273	331	211	236	200	189	178	73	144
W19	2330	295	187		197	92		163	12	115	71		
N20	2657	87*			180*			262*		302*			
N21	2683	165			292			318		359			
CZN ^Δ	4050	171			146			132		115			
CZC ^Δ	4050	185			192			147		136			
CZS ^Δ	4050	287			275			228		149			

*Run 9.

**Run 10* - nozzle blocked.

Remaining data: run 10 - nozzle clear.

^ΔPorts in top of combustor, west wall, near entrance to convective zone.

Table C.5 - CO measurements, ppm volume, dry gas basis

Port	Height mm	Probe position											
		200 mm	400 mm	600 mm	800 mm								
A17	1540	6333*	8737**	7449	5984*	8297**	7338	5568**	7756**	6213	5068*	6505**	4961
E17	1540	6202	8639	7761	6056	8356	5563	6286	5044	5332	6064	5231	4692
I17	1540	5156	6118	6576	5623	5445	5563	4153	5044	5332	4650	4031	4692
W17-N	1540	6507*	5262**		6033*	6234**		8503**	5765**		7094*	4224**	
W17-S	1540	6459	8448		6657	8763		6788	8603		5612	6390	
S17.5	1744	8266**			7847**			7254**			6396**		
S18	1835	6601	8157	6170	6788	7558	6416	6392	6539	5226	5980	4741	4116
W19	2330	5971	6831		5247	5694		5008	3232		4042	2298	
N20	2657	3761*			4562*			4720*			4217*		
N21	2683	3169			2533			2897			3352		
CZN ^Δ	4050	2193			1755			1484			1201		
CZC ^Δ	4050	2986			2032			1797			1659		
CZS ^Δ	4050	3340			2507			2109			1868		

*Run 9.

**Run 10* - nozzle blocked.

Remaining data: run 10 - nozzle clear.

^ΔPorts in top of combustor, west wall, near entrance to convective zone.